Electroweak Hall Effect of Neutrino and Coronal Heating

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(Dated: March 26, 2015)

Abstract

The inversion of temperature at the solar corona is hard to understand from classical physics, and the coronal heating mechanism remains unclear. The heating in the quiet region seems contradicting with the thermodynamics and is a keen problem for physicists. A new mechanism for the coronal heating based on the neutrino radiative transition unique in the corona region is studied. The probability is enormously amplified by an electroweak Chern-Simons form and overlapping waves, and the sufficient energy is transfered. Thus the coronal heating is understood from the quantum effects of the solar neutrino.

INTRODUCTION

The experiments on solar neutrino [1–4] proved that the nuclear fusion is the heat source in the core and the neutrinos have masses. Now, there remains a problem on the temperature of the solar corona. The sun's temperature is 10^8 K at the core, and 6×10^3 K at the solar sphere. That is $10^6 - 10^7$ K at the corona region [5, 6], which is higher by $10^3 - 10^4$ than that at the solar surface, despite the fact that the heat source is in the core. There have been many studies based on the electromagnetic interactions, using magnetic-acoustic waves, Alfven waves, micro-flare reconnection, and others, which have shown that these regions are not static but dynamic of revealing many activities [7]. New observation using satellite shows also these activities. The corona is heated not only in these active regions but also in the quiet regions, which seems contradicting with the thermodynamics. To find the heat source in the quiet region is a fundamental physical problem. Hence we focus our study on the quiet region in the present paper.

Because the neutrino is produced in the nuclear fusion, about 10% of the initial energy produced at the core is carried by the neutrino. Its interaction with matter is quite weak of the cross section $G_F^2 E_\nu m_{\text{proton}}$ and of a mean free path longer than 10^{25} m at the density, $n = 10^{20}$ m^{-3}, and $E_\nu = 1$ MeV. Neutrinos have been considered not to interact with the corona. It is noted that these values are obtained using the transition rate obtained from Fermi's golden rule and its equivalent formula of S-matrix in the relativistic field theory, which are valid only if the initial and final waves do not overlap [8] and behave like particles. The neutrino and photon are waves of large extensions in the corona, and the transition probability P gets modified and has a new term $P^{(d)}$ in addition to the standard T-linear term

$$P = \Gamma T + P^{(d)}, \tag{1}$$

where T is the time-interval between the initial and final states [9–11]. The term $P^{(d)}$ has origins in the overlap of the waves and consequently is very different from Γ and becomes huge for the neutrino radiative process in the corona owing to the tiny photon's effective mass. Γ in the neutrino-photon interactions is ignorable due to Landau-Yang-Gell-Mann theorem [12–14], and by a tiny transition magnetic moment [15, 16], but due to $P^{(d)}$ the neutrino radiative transition occurs [11].

Here we consider $P^{(d)}$ of the neutrino radiative process in the corona region. The corona has a magnetic field and free electrons, which reveals the Hall effect, which is expressed in quantum theory by a Chern-Simons form of the electromagnetic potential. The form is proportional to $\frac{n_e}{B}\frac{e^2}{h}$, where n_e is the electron density and B is the magnetic field, and agrees with a topological invariant. That is materialized as a macroscopic quantum phenomenon such as the quantized Hall effect in two-dimensional semi-conductors [17, 18], and is used as the standard of the electric resistance.

INDUCED ELECTROWEAK CHERN-SIMONS TERM AND TRANSITION PROBABILITY

In the corona, the Lamor oscillation in a mean free path is larger than unity, $\omega_B \times \frac{l^e_{\text{mfp}}}{v} > 1$, where $\omega_B = \frac{eB}{m_e}$, l^e_{mfp} and v is the mean free path and the velocity of the electrons. The electrons are expressed by Landau levels, which differs from a weak B expansion [19].

A system of electrons, photons, and neutrinos in the external magnetic field in the 3rd-direction are described by the Lagrangian

$$\mathcal{L} = \mathcal{L}_0 + \frac{G_F}{\sqrt{2}}\bar{\psi}_e(x)\gamma_\mu(1-\gamma_5)\psi_e(x)\bar{\nu}_e(x)\gamma_\mu(1-\gamma_5)\nu_e(x) + ej_\mu(A^\mu_{\text{ext}} + A^\mu),$$

$$\mathcal{L}_0 = \bar{\nu}_i(x)(p^\mu\gamma_\mu(1-\gamma_5) - m_i)\nu_i(x) + \bar{\psi}_e(x)(p^\mu\gamma_\mu - m_e)\psi_e(x) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \tag{2}$$

where the magnetic field is expressed by A^μ_{ext}, and $\nu_e(x)$ is the electron neutrino. The neutral current interaction is symmetric in all flavours and does not contribute to the neutrino radiative transitions and were ignored in Eq. (2). Expanding $\psi_e(x)$ with eigen functions of including A^μ_{ext}, and integrating them, we find the effective Lagrangian [18, 20, 21],

$$\mathcal{L}_{\text{int}} = \frac{\nu^{(4)}}{2\pi}\epsilon^{\alpha\beta\gamma}\tilde{A}_\alpha\partial_\beta\tilde{A}_\gamma + O(\tilde{F}^2_{\alpha\beta}); \ \alpha,\beta,\gamma = (0,1,2), \tag{3}$$

where $\nu^{(4)} = \frac{2\pi\hbar n_e}{eB}$ is the filling factor of Landau levels, and $\epsilon^{\alpha\beta\gamma}$ is the anti-symmetric tensor, and

$$\tilde{A}_\alpha = eA_\alpha(x) + \frac{G_F}{\sqrt{2}}J_\alpha(x), \tag{4}$$

$$J_\alpha(x) = \bar{\nu}_e(x)\gamma_\alpha(1-\gamma_5)\nu_e(x), \tag{5}$$

$$\tilde{F}_{\alpha\beta} = F_{\alpha\beta} + \frac{G_F}{\sqrt{2}}(\partial_\alpha J_\beta - \partial_\beta J_\alpha). \tag{6}$$

$\nu_e(x)$ is the superposition $\nu_e(x) = \sum_i U_{ei}\nu_i(x)$ of three mass eigenstates $\nu_i(x)$; $i = 1 - 3$ and a mixing matrix U. It follows that

$$J_\alpha(x) = g_{ij}\nu_i(x)\gamma_\alpha(1 - \gamma_5)\nu_j, \qquad (7)$$

$$g_{ij} = U_{ei}^* U_{ej}.$$

Thus Eq. (3) leads a neutrino radiative transition, which has the following unusual properties: that is Lorentz non-invariant; the strength is proportional to $eG_F\nu^{(4)}$. The coupling strength is a topological invariant which satisfies a low energy theorem and remains the same in systems of disorders at finite-temperature [18, 20, 21].

A radiative transition $\nu_i \to \gamma + \nu_j$ takes place, since the neutrino mass difference is larger than the photon's effective mass determined by the plasma frequency $m_{\gamma,\text{eff}} = \hbar\omega_p$. The event that γ is detected or interacts with others at T and ν_j escapes, is studied. The LSZ formula [22, 23] is extended to an S-matrix, $S[T]$ of satisfying this boundary condition [9–11] at the finite-time interval. Because $[S[T], H_0] \neq 0$, $S[T]$ couples with the final states of continuous spectrum of the kinetic energy different from the initial kinetic energy, which is caused by the overlap of the waves. Thus the space time symmetry of the free Lagrangian such as the conservation law of the kinetic energy and manifest Lorenz invariance are partly broken in $P^{(d)}$. Being non-invariant, $P^{(d)}$ can be much larger in magnitude than the invariant as in the example; $|\vec{p}_\nu|^2 \gg E_\nu^2 - (\vec{p}_\nu)^2 = m_\nu^2$, at the high energy. Γ is Lorentz invariant and is proportional to m_ν^4, which is negligibly small for the neutrino [24–26], whereas $P^{(d)}$ is proportional to a lower power in m_ν of much larger magnitude.

The amplitude is written as $\mathcal{M} = \int d^4x \, \langle \gamma, \nu_j | (-L_{\text{int}}(x)) | \nu_i \rangle$, for a neutrino prepared at a time $T_{\nu_i} = 0$, and a photon interacting at a space-time position $(T_\gamma, \vec{X}_\gamma)$ and an unmeasured-neutrino, which are expressed in the form $|\nu_i\rangle = |\vec{p}_{\nu_i}, T_{\nu_i} = 0\rangle$, $|\nu_j, \gamma\rangle = |\nu_j, \vec{p}_{\nu_j}; \gamma, \vec{p}_\gamma, \vec{X}_\gamma, T_\gamma\rangle$, and the time t is integrated in the region $0 \leq t \leq T_\gamma$. The size of photon wave function, σ_γ, is estimated later. After the straightforward but tedious calculations, the details of which were given in Refs. [9, 10], we have the total probability in the form

$$P = N_2 \int \frac{d^3 p_\gamma}{(2\pi)^3 E_\gamma} (\tilde{p}_{\nu_i} \cdot \tilde{p}_\gamma)(\tilde{p}_{\nu_i} \cdot \tilde{p}_\gamma - \tilde{p}_\gamma^2) \left[\tilde{g}(\omega_\gamma, T) + G_0 \right], \qquad (8)$$

where $\tilde{p} = (p_0, p_1, p_2)$, $N_2 = 8T(\frac{\nu^{(4)}eG_F g_{ij}}{2\pi})^2 \frac{\hbar\sigma_\gamma}{\epsilon_0 E_{\nu_i}}$, $L = cT$, $T = T_\gamma$ is the length of decay region. The function $\tilde{g}(\omega_\gamma, T)$, which is given in Refs. [9, 10], is characterized by a phase factor $e^{i\omega_\gamma(t_1 - t_2)}$ of the correlation function of the angular velocity $\omega_\gamma = \hbar\frac{m_{\gamma,\text{eff}}^2 c^4}{2E_\gamma}$, shows

4

$P^{(d)}(\gamma)$, and G_0 shows ΓT and is negligible now. The phase space for $P^{(d)}(\gamma)$ is different from that of ΓT, and is derived from the causality condition. It follows for the general cases of two neutrino flavour and an angle $\Theta_{\vec{B},\vec{p}_{\nu_1}}$ between the magnetic field and $\vec{p}_{\nu_1}$ that

$$P^{(d)}(\gamma) \approx P^{(d)}_{\mathrm{asym}}(\gamma)\frac{T}{T_0}, \ T_0 = \frac{1}{\omega_\gamma}; \ \omega_\gamma T < 1, \tag{9}$$

$$P^{(d)}_{\mathrm{asym}}(\gamma) = \eta\frac{\alpha}{5\pi}\left(\frac{G_F}{(c\hbar)^3}E^2_{\nu_1}\right)^2\frac{\delta m^2_\nu}{m^2_{\gamma,\mathrm{eff}}}\left(\frac{\nu^{(4)}}{2\pi}\right)^2\sigma_\gamma; \ \omega_\gamma T \geq 1, \tag{10}$$

$$\eta = \cos^2\Theta_{\vec{B},\vec{p}_{\nu_1}}\cos^2\theta_{12},$$

where θ_{12} is a mixing angle between the flavour and mass eigenstates, and the heaver neutrino corresponds to the electron neutrino if $\theta_{12} = 0$. For the three neutrino cases, η becomes a more complicated expression of an essentially the equivalent result.

The state vector of revealing the constant probability, $P^{(d)}(\gamma)$, in the vacuum, is a superposition of the parent and daughters of almost time independent weight, and is like a stationary state. In the environment of many atoms or molecules, on the other hand, the produced photon interacts with them and loses its energy easily. Consequently, the probability of the neutrino to lose the energy is given by the product $P^{(d)}(\gamma) \times P_\gamma$, where P_γ is governed by QED and is order unity. Hence, the energy is transfered, and the environment gains the energy and is heated. It must be noted that the diffractive probability for the neutrino is determined by ω_ν and is much smaller than that of the photon, in the situation $m_\nu \gg m_\gamma$ of the paper, and is ignored.

CORONAL HEATING AND SOLAR WIND ACCELERATION

Equations (8), (9), and (10) are applied to the solar corona. Parameters are taken from Ref. [27] and the filling factor $\nu^{(4)}$, and the wave packet size $\sigma_\gamma = (l^c_{\mathrm{mfp}})^2$, where l^c_{mfp} is the mean free path of the proton or electron are computed and used. The photon's effective mass $m_{\gamma,\mathrm{eff}}$ becomes smaller than the neutrino mass squared difference. The function $\tilde{g}(\omega_\gamma, T)$ at the non-asymptotic region is used. Using these values, we have

$$P^{(d)}(\gamma) \approx 10^{-3}; \ E_\nu = 10 \text{ MeV}, \tag{11}$$

the total energy transferred to the corona

$$E^{\mathrm{transfer}} = P^{(d)}(\gamma) \times N_\nu \approx 5 \times 10^5 \text{ erg cm}^{-2}\text{s}^{-1}, \tag{12}$$
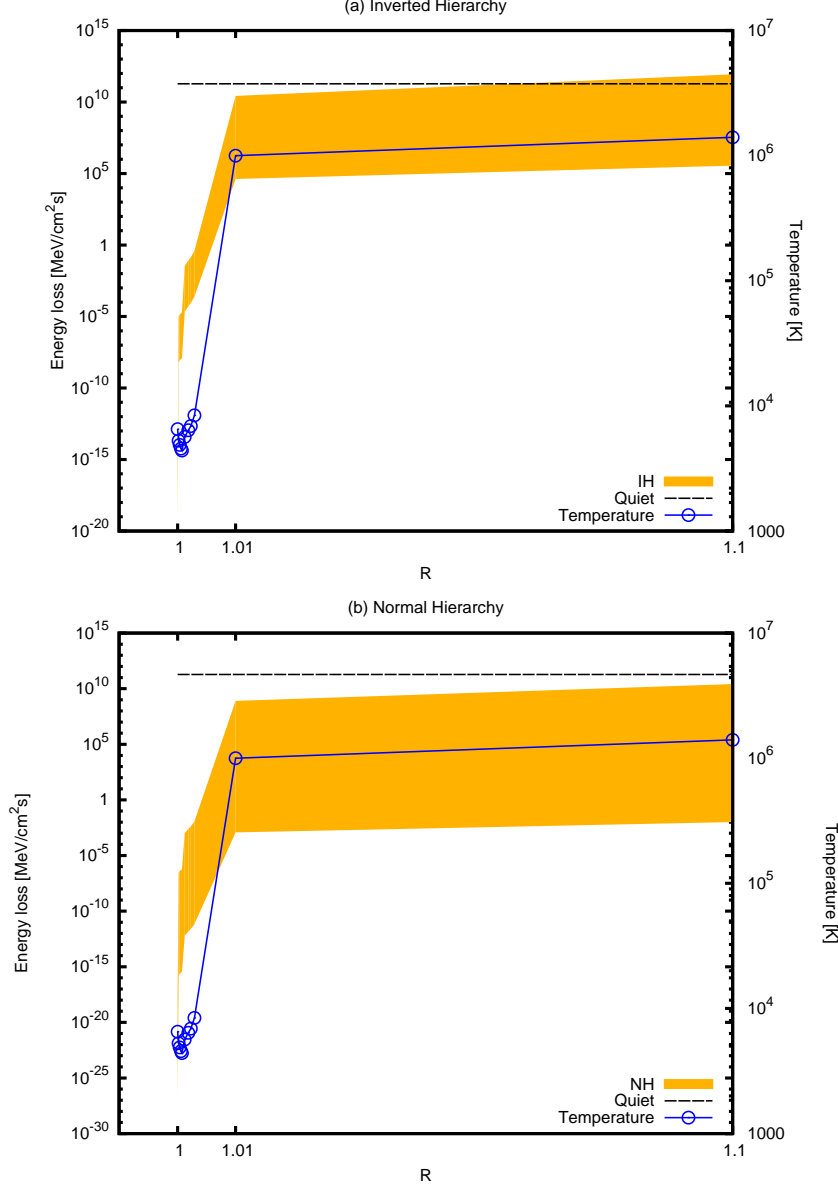
FIG. 1. R dependence of the transferred energy to the corona [MeV/cm^{2}s] is compared with the energy necessary to heat the corona at $R = 1.1R_\odot$. Temperature rising steeply at around $R = 1.01R_\odot$ is also shown. (a) is for the inverted mass hierarchy and supplies the sufficient energy, but (b) for the normal mass hierarchy does not supply the sufficient energy.

where N_ν is the energy flux of the neutrino. In Fig. 1, E^{transfer} is given as a function of the radius $R/R_\odot$, $R_\odot =$ the slar radius, and compared with the estimated energy at $R = 1.1R_\odot$ [28], and the temperature. The mass differences are known but the absolute masses and mass hierarchy are unknown. For the inverted mass hierarchy, the neutrino mass-squared differences $\delta m_\nu^2 = 2.52 \times 10^{-3}$ eV^2(IH) and for the normal mass hierarchy

$\delta m_\nu^2 = 7.53 \times 10^{-5}$ eV^2(NH) are substituted and the absolute mass are varied. The energy for IH is in accord with the observation, however the maximum value for NH is 1/100 of the observation. The normal mass hierarchy would be rejected, even though there are ambiguities on the magnetic field, the electron density, and the temperature. Because the electron density decreases steeply, the probability $P^{(d)}(\gamma)$ becomes the value Eq. (11) rapidly in the corona region, and the temperature rises steeply, which is in agreement with the observation. Thus the heating of the quiet corona is understood from the neutrino radiative transitions.

In a corona hole, the electron density is low and the magnetic field is high, and $P^{(d)}$ is not large at the height of the transition region. However the effect becomes stronger because the magnetic field is parallel to the neutrino up to a high altitude, and an acceleration of the solar wind becomes higher, which is in accord with the observation. A recent observation of a density modulation of the plasma wave [29] also agrees with the extremely slow angular velocity $(\omega_\gamma)^{-1} \approx 10^2$ s in this region.

The probability $P^{(d)}(\gamma)$ varies following the change of B, and influences the solar constant and other related phenomena. B is large in the core of the sun spot, the rate of energy loss is correlated with the sun spot number. A correlation between the small variation of the solar constant of the order of Eq. (11) or slightly smaller value and the sun spot number observed in recent measurements appears.

In the active region where the present conditions hold, the diffractive probability is important as well.

Earth Ionosphere and radiation belt

Ionosphere in the earth is also a plasma of low density and weak magnetic field, so is affected by the electroweak Hall effect. Substituting values 10^{-5} T and 10^{11} m^{-3} for the magnetic field and electron density, we have

$$P^{(d)}(\gamma) = 10^{-7}, \tag{13}$$

which is much smaller than the value at the solar corona Eq. (11). The neutrino flux is lower by a factor 10^{-6} due to the large distance, and the energy released from the neutrino to atoms becomes small. On the other hand, the temperature of lights from the sun is

5800K and is higher than that in the ionosphere 1000 K, which may be caused mainly by photochemical reactions. It may be hard to see the temperature variation caused by the neutrino in the ionosphere. Nevertheless the diagonal component of the interaction Lagrangian in the neutrino flavour, causes the neutrino current to induce the electric or magnetic fields. Such time-dependent variation of the magnetic field around 20 nT observed at the earth surface may be connected with the solar neutrino through the electroweak Hall effects in the earth. These will be presented in a forthcoming work.

SUMMARY AND IMPLICATIONS.

The new coronal heating mechanism is based on the following: **(1)** massive neutrino, **(2)** electroweak Hall effect of the dilute plasma in the magnetic field expressed by the effective interaction Eq. (3), and **(3)** the diffractive component of the transition probability $P^{(d)}(\gamma)$. They lead the large coupling strength, $\frac{\nu^{(4)}}{2\pi}$, the tiny photon's effective mass $m_{\gamma,\text{eff}} = \hbar\omega_p$, and the large wave packet σ_γ, and make $P^{(d)}(\gamma)$ to be $10^{-3} - 10^{-4}$. Due to $P^{(d)}(\gamma)$, the neutrino which arrives the corona region maintaining the initial energy, decays and loses the energy. Its probability $P^{(d)}(\gamma) \times P_\gamma$ agrees with $P^{(d)}(\gamma)$, because $P_\gamma \approx 1$. Hence the average energy $P^{(d)}(\gamma)E_\nu/2$, which is in accord with the observation given in Fig. 1, is transfered to the corona gas. $P^{(d)}(\gamma)$ was enhanced enormously in the corona region and the temperature rises steeply. The neutrinos gives the heat to the solar corona, and a possible electromagnetic effect to the earth through ionosphere.

The probability $P^{(d)}(\nu)$ for the neutrino is determined by the neutrino mass and σ_ν, which are assumed $m_\nu \approx 10^{-3}$ eV and $\sigma_\nu \approx 10^{-28}$ m^2, and is much smaller than those of the photon. Hence a reduction of the neutrino flux is negligible unless $m_\nu \approx 0$. The neutrino oscillation experiments measure the T-dependent variations of the neutrino flux derived from the components ΓT. The large $P^{(d)}(\gamma)$ in the dilute electron gas in the magnetic field is not in contradiction with existing neutrino phenomena and experiments. A correlation of the neutrino flux with the sun spot number may be too small to measure using the current ground detector.

It would be worthwhile to test the present mechanism using ground experiments with nuclear reactors, high energy accelerators, or others.

A new quantum phenomenon of the neutrinos radiative decays was derived and shown

to give the heat source to the solar corona, and other effects in the earth ionosphere. Thus the neutrino produced in the core gives the energy into the solar corona. The mechanism for the former is the nuclear fusion and that for the latter is the electroweak Hall effect and the diffractive probability.

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